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Exploring Nuclear Matter at Neutron Star Core Densities

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Substantial experimental and theoretical efforts worldwide are devoted to explore the phase diagram of strongly interacting matter. At top RHIC and LHC energies, the QCD phase diagram is studied at very high temperatures and very low net-baryon densities. These conditions presumably existed in the early universe about a microsecond after the big bang. For larger net-baryon densities and lower temperatures, it is expected that the QCD phase diagram exhibits a rich structure such as a critical point, a first order phase transition between hadronic and partonic matter, or new phases like quarkyonic matter. The experimental discovery of these prominent landmarks of the QCD phase diagram would be a major breakthrough in our understanding of the properties of nuclear matter. The Compressed Baryonic Matter (CBM) experiment will be one of the major scientific pillars of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. This includes the study of the equation-of-state of nuclear matter at neutron star core densities, and the search for the deconfinement and chiral phase transitions. The CBM detector is designed to measure rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics. Most of these particles will be studied for the first time in the FAIR energy range. In order to achieve the required precision, the measurements will be performed at very high reaction rates of 1 to 10MHz. This requires very fast and radiation hard detectors, and a novel data read-out and analysis concept based on free streaming front-end electronics and a high-performance computing cluster for online event selection. The layout, the physics performance, and the status of the proposed CBM experimental facility have been discussed in the present manuscript.

Key Words : High-Energy Heavy-Ion Collisions; Qcd Phase-Diagram

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Probing QCD Matter With Heavy-Ion Collisions

High-energy heavy-ion collision experiments provide the unique possibility to create and investigate extreme states of strongly-interacting matter and therefore, address fundamental aspects of QCD:

- the equation-of-state of strongly interacting matter at high temperatures and high net-baryon densities,
- the microscopic structure and the properties of strongly interacting matter as function of temperature and baryon density, such as hadronic and partonic phases, the location of phase transitions and critical points,
- the in-medium modifications of hadrons which might signal the onset of chiral symmetry restoration.

The nuclear matter equation-of-state plays an important role for the dynamics of core collapse supernova and for the stability of neutron stars. In type II supernova explosions, symmetric nuclear matter is compressed to 2-3 times saturation density ρ_0. These conditions are realized in heavy-ion collisions at beam energies around 1 A GeV, although the temperatures reached in nuclear collisions are higher than those in the core of a supernova. Heavy-ion experiments at BEVALAC/SIS18 discovered the collective flow of nucleons, and studied in detail the production of pions and strange particles. In particular, the data on strangeness production and on the elliptic flow of light fragments obtained at SIS18 provided evidence for a soft nuclear matter equation-of-state around twice saturation density. Moreover, pioneering studies of electromagnetic radiation from the fireball via the measurement of electron-positron pairs have been performed at the BEVALAC in order to obtain information on the in-medium properties of vector mesons. Precision measurements of di-electron production in proton-proton, proton-nucleus and nucleus-nucleus collisions have been and are being performed with the second generation HADES spectrometer at SIS18, unraveling the important role of baryonic resonances in dilepton production.

The experiments at BNL-AGS measured the yields and momentum spectra of various particle species in heavy-ion collisions, and established the scenario of an expanding thermalized source with a simultaneous chemical freeze-out of all particles. A major achievement of the experiments at AGS was the measurement of the excitation function of collective flow of protons as a probe of the equation-of-state of dense nuclear matter.

Experiments at CERN-SPS extended the list of hadrons observed in heavy-ion collisions up to multi-strange hyperons, and confirmed the picture of a chemically equilibrated fireball. The particle yields and event-wise fluctuations measured in Pb+Pb collisions exhibit intriguing features at low SPS energies, which have been interpreted as signatures for the onset of deconfinement. The observation of a strong suppression of the charmonium yield in central collisions supported the idea of Debye screening of charmonium in quark-gluon matter. Measurements of electron-positron pairs and muon pairs found an enhanced dilepton yield at invariant masses between 0.2 GeV/c^2 and 1 GeV/c^2, an effect which is interpreted as a contribution from ρ mesons with modified in-medium masses.

Experiments at RHIC made three major discoveries in heavy-ion collisions at top energies: a large azimuthal anisotropy of particle emission in noncentral collisions (elliptic flow), the scaling of the anisotropy with the number of constituent quarks, and the suppression of high-energetic particles traversing the medium ("jet-quenching"). These observations have been interpreted as evidence for the creation of partonic matter. In order to search for the QCD critical point and for the first order phase transition, the STAR experiment at RHIC performed a beam energy scan from top energy of $\sqrt{s_{NN}}$ = 200 GeV down to $\sqrt{s_{NN}}$ = 7.7 GeV (STAR Collaboration, 2014). It was found that the effects observed at high energies (elliptic flow, quark number scaling and jet quenching) more or less continuously disappeared with decreasing energy, and no indication for a critical point or a phase transition was seen. However, the data at low beam energies suffer from statistics, as the luminosity decreases strongly with decreasing beam energy.

At LHC, heavy-ion collisions were studied at an energy which is almost 14 times higher than the top RHIC energy. It was found, that the the charged-particle density at midrapidity in central Pb+Pb collisions is 2.2 times higher than in central Au+Au collisions at RHIC, and the initial energy density is about a factor of 3 higher (Kryshen *et al.*, 2013). The fireball volume increases by a factor of 2 from RHIC to LHC, and the fireball lifetime by about 20%. The mean collective velocity of the transverse expansion of the fireball was found to be 10% higher at LHC than at RHIC. The LHC experiments confirmed the large elliptic flow measured at from RHIC, but did not reproduce its constituent quark number scaling for high transverse momenta. Moreover, a significant deviation from the thermal model has been observed by ALICE at LHC. A model with a chemical freeze-out temperature of T_{ch}=164 MeV, extrapolated from the RHIC data, agrees with the particle ratios including multi-strange hyperons, but misses the p/π and the Λ/π ratios. The suppression of high-p_T hadrons (jet-quenching) was found to be stronger (around $p_T \approx$6 GeV/c) at LHC than at RHIC energies, slowly increasing at higher p_T. The suppression of J/ψ mesons as function of participants is less pronounced at LHC than at RHIC, an effect which is interpreted as a consequence of regeneration of $c\bar{c}$ pairs at higher energies. The suppression of hidden charm due to color-screening effects was an early prediction for a signature of deconfinement. The measurement of proton-nucleus collisions at LHC resulted in a surprise: In high-multiplicity p+Pb collisions an elliptic flow pattern was observed, exhibiting a mass ordering for identified particles as function of p_T similar to Pb+Pb in accordance with hydrodynamical models. The heavy-ion experiments at LHC will be continued after detector upgrades for measurements at higher luminosity.

At LHC and top RHIC energies, strongly interacting matter is created at very high temperatures and almost zero baryon chemical potential. Such conditions existed in the early universe several microseconds after the big bang. Lattice QCD calculations predict for zero baryon chemical potential a chiral phase transition at a temperature of 150- 160 MeV (Borsanyi *et al*., 2010; Basavov *et al*., 2012). In this region of the phase diagram the transition is predicted to be a smooth crossover from partonic to hadronic matter (Aoki *et al*., 2006). At finite baryon chemical potentials and lower temperatures, model calculations predict structures in the QCD phase diagram like a critical endpoint followed by a first order phase transition (Luecker *et al*., 2013). Fig. 1 illustrates the conjectured phases of nuclear matter and their boundaries in a diagram of temperature versus baryon chemical potential (Fukushima and Hatsuda, 2011). At large baryon chemical potentials, the phase diagram features structures such as a critical point, and transitions between various phases such as hadronic matter, quarkyonic matter, quark-gluon plasma and color superconductors. The experimental discovery of these landmarks of the QCD phase diagram would be a major breakthrough in our understanding of the properties of nuclear matter. Equally important is quantitative experimental information on the properties of hadrons in dense matter which may shed light on chiral symmetry restoration and the origin of hadron masses.

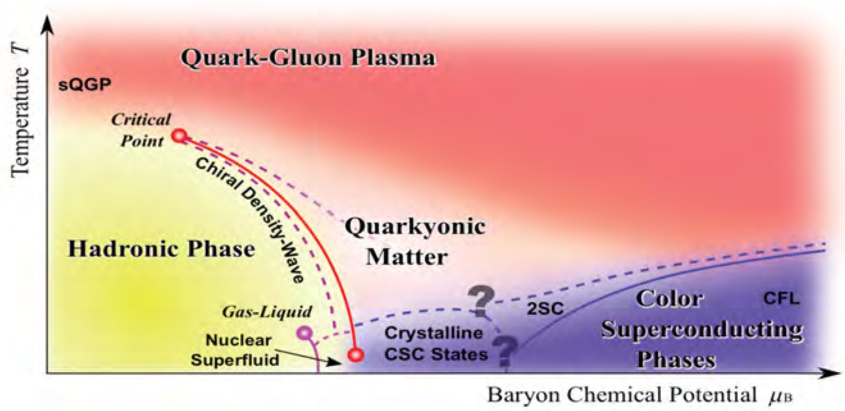


Fig. 1: Sketch of the phase diagram for nuclear matter. (Fukushima and Hatsuda, 2011)

Several experimental programs are devoted to the exploration of the QCD phase diagram at large baryon-chemical potentials. The STAR collaboration at RHIC plans a second beam energy scan to improve the statistical significance of the data taken in the first series of measurements (STAR Collaboration, 2014). At the CERN-SPS, the NA61/SHINE experiment continues to search for the first-order phase transition using light and medium size beams (Laszlo *et al*., 2007). At the Joint Institute for Nuclear Research (JINR) in Dubna, a fixed target experiment is being installed at the Nuclotron to study heavy-ion collisions at gold-beam energies up to 4.5 A GeV. Moreover, a collider facility is under discussion at JINR (NICA, 2014). However, due to luminosity limitations these experiments are constrained to the investigation of bulk observables, and suffer from statistics for rare diagnostic probes. In order to overcome this limitation, the

Compressed Baryonic Matter (CBM) experiment is under development at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt. This new generation heavy-ion collision experiment is designed for the measurement of bulk and rare probes with unprecedented precision. A survey of the theoretical concepts and the experimental programs devoted to the exploration of the QCD phase diagram with focus on high baryon densities is given in the CBM Physics Book (CBM Physics Book, 2011). In the next chapter the FAIR facility will be briefly outlined.

The future Facility for Antiproton and Ion Research (FAIR)

The layout of the future international Facility for Antiproton and Ion Research (FAIR) in Darmstadt is shown in Fig. 2.

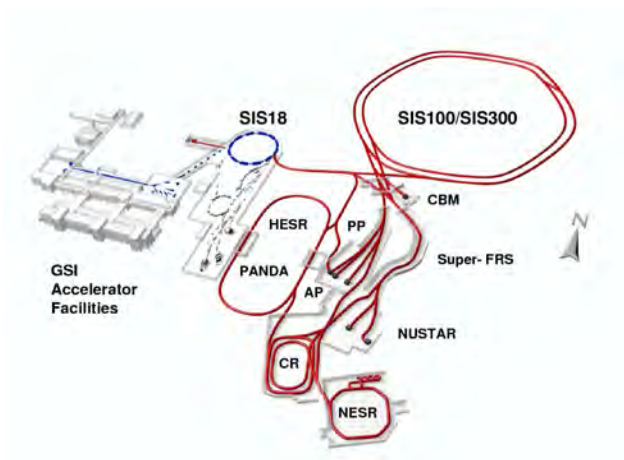


Fig. 2: Layout the future Facility for Antiproton and Ion Research (FAIR) (FAIR Report, 2006)

FAIR will provide unique research opportunities in the fields of nuclear, hadron, atomic and plasma physics (FAIR Report, 2006). The double-ring synchrotron (SIS100 and SIS300) will deliver primary beams with very high intensities (protons up to 90 GeV, Uranium up to 35 AGeV, nuclei with Z/A = 0.5 up to 45 AGeV). The primary beams can be converted into very intense secondary beams of ions and antiprotons. High-intensity secondary beams of rare isotopes will be produced with the Superconducting Fragment Separator (SFRS). Their properties will be studied using the various experimental facilities of the NuSTAR collaboration. Intense beams of antiprotons will be accelerated and cooled in the High-Energy Storage Ring (HESR), and will be used for hadron physics experiments with the PANDA detector. Furthermore, there are experimental setups for Plasma Physics (PP) and Atomic Physics (AP). High energy nucleus-nucleus collisions will be investigated with the Compressed Baryonic Matter (CBM) detector. FAIR will be financed by a joint international effort of so far ten member states. The Federal Republic of Germany together with the State of Hesse is the major contributor to the construction, the current nine international partners - Finland, France, India, Poland, Romania, Russia, Slovenia, Sweden and the United Kingdom - cover about 30% of the construction costs. The civil construction has started, the accelerator development is well under way. The first superconducting dipole magnet for SIS100 has been delivered, and a fast ramping superconducting SIS300 prototype dipole magnet has been successfully tested.

The CBM Physics Program

In central Au+Au collisions at FAIR SIS300 energies the nuclear fireball will be compressed to about 10 times saturation density ρ_0, even at SIS100 energies (11 A GeV for Au beam) about 6 times ρ_0 is reached according to transport calculations. At such densities, the nucleons will start to melt and to dissolve into their constituents. This phenomenon is illustrated in Fig. 3 which depicts the particle abundance as a function of density inside a neutron star as calculated with a Nambu Jona-Lasinio (n3NJL) model (Orsaria *et al*., 2013). Above a density of 4 - 5 ρ_0 the nucleons start to melt into quarks forming a mixed phase of hadrons and quarks. Above a density of 8-9 ρ_0 pure quark matter is formed. Due to the repulsive vector coupling between the quarks, the model is able to describe neutron stars with 2 solar masses. Heavy-ion beams at FAIR energies are well suited to explore the properties of strongly interacting matter at neutron star core densities. The experimental challenge is to identify diagnostic probes of the dense phase of the fireball which is transiently formed in the collision. In experiments performed so far at AGS, at low SPS energies, or at very low RHIC energies, mainly particles have been measured which are created at freeze-out where the density already has dropped below saturation density. The focus of the CBM experiment at FAIR is to study messengers from the dense fireball such as hadrons containing charm quarks, multiple strange hyperons, and dilepton pairs. The CBM research program includes:

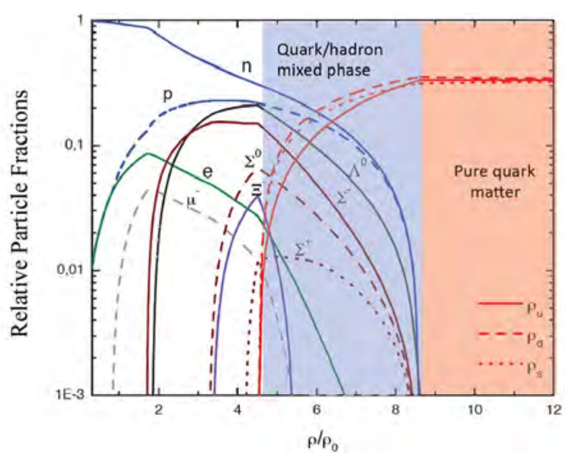


Fig. 3: Particle population in a neutron star calculated with a Nambu Jona-Lasinio (n3NJL) model with repulsive vector interactions. The model is able to describe neutron stars with 2 solar masses and radii between 12 and 13 km (Orsaria *et al*., 2013)

- The equation-of-state of nuclear matter at neutron star densities. We plan to measure the excitation functions of multi-strange hyperons in Au+Au collisions. At lower FAIR energies, Ξ and Ω hyperons are produced in sequential collisions involving kaons and Λs and therefore, are sensitive to the density in the fireball (no data available). Moreover, we will measure the excitation function of the collective flow of hadrons which is driven by the pressure created in the early fireball. Only the proton flow excitation function was measured at AGS.

- Modifications of hadron properties dense baryonic matter as a signature for chiral symmetry restoration. The relevant observable is the in-medium mass distribution of vector mesons decaying in lepton pairs in heavy-ion collisions at energies from 2 to 35 A GeV, and for different collision systems (no data available). Leptons are penetrating probes carrying the information out of the dense fireball. Moreover, we will measure the yields and transverse mass distributions of charmed mesons in heavy-ion collisions as function of energy (no data available at FAIR energies).

- Phase transitions from hadronic matter to quarkyonic or partonic matter at high net-baryon densities, and the critical point of QCD matter. We will measure the excitation function of yields, spectra, and collective flow of strange particles in heavy-ion collisions from 6 to 45 A GeV. Low statistics data are available from AGS, SPS-NA49 and from the RHIC beam energy scan. We will measure the excitation function of yields, spectra and collective flow of charmed particles in heavy-ion collisions from 6-45 A GeV (no data available). We will measure the excitation function of yields and spectra of lepton pairs in heavy-ion collisions from 6 to 45 A GeV at invariant masses up to charmonium (no data available). We will measure event-by-event fluctuations of baryons and strangeness in heavy-ion collisions with high precision as function of beam energy from 6 to 45 A GeV. Low statistics data have been measured by SPS-NA49.

- Hypernuclei, strange dibaryons and massive strange objects. Theoretical models predict that single and double hypernuclei, strange dibaryons and heavy multi-strange short-lived objects are produced via coalescence in heavy-ion collisions with the maximum yield in the region of SIS100 energies. We will measure the decay chains of single and double hypernuclei in heavy ion collisions at SIS100 energies. Few events have been observed in reactions with K^- beams. We will search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects. If these multi-strange particles decay into charged hadrons including hyperons they can be identified via their decay products (no data available).

- Charm production mechanisms, charm propagation, and in-medium properties of charmed particles in (dense) nuclear matter. We will measure open charm in proton-nucleus collisions at FAIR energies (no data available). Moreover, we will measure charmonium production in nucleus-nucleus collisions at different energies (no data available below top SPS energies).

The Compressed Baryonic Matter (CBM) Experiment

The CBM detector is designed as a multi-purpose device which will be able to measure hadrons, electrons and muons in heavy-ion collisions. The experimental challenge is to select rare events in nucleus-nucleus collisions with charged particle multiplicities of about 1000 per central event. In order to perform high-precision measurements of rare probes the experiment should run at event rates of 100 kHz up to 10 MHz. Because of the complicated decay topology of particles like Ω hyperons or D mesons, no simple trigger signal can be generated, so the events have to be reconstructed and selected online by fast algorithms running on a high-performance computing farm. Therefore, the data readout chain is based on a free streaming frontend electronics which delivers time-stamped signals from each detector channel without event correlation. The experimental challenge is to reconstruct and to select events at reaction rates up to 10 MHz which are required for high-precision charmonium measurements. The reconstruction algorithms are tuned to run at high speed on modern many-core CPU architectures. A sketch of the CBM experimental setup is shown in Fig. 4. The detector system features a fixed target geometry accepting polar emission angles between 2.5 and 25 degrees in order to cover midrapidity for symmetric collision systems at beam energies between 2 and about 40 A GeV. The setup comprises the following components: a large aperture superconducting dipole magnet, a Silicon Tracking System (STS) based on double-sided silicon microstrip sensors arranged in 8 stations inside the magnetic field, a Micro Vertex Detector (MVD) consisting of 4 layers ultra-thin silicon pixel sensors (monolithic active pixel sensors), a time-of flight wall (TOF) based on multigap resistive

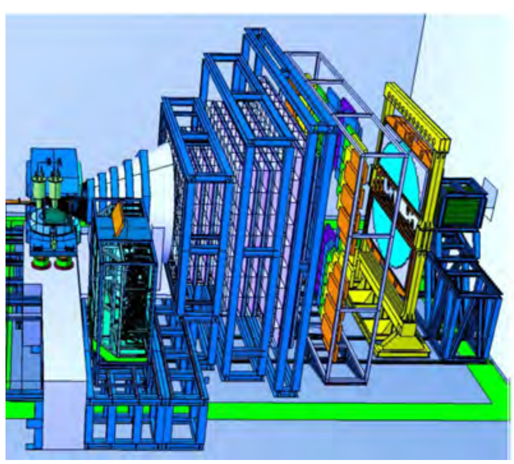
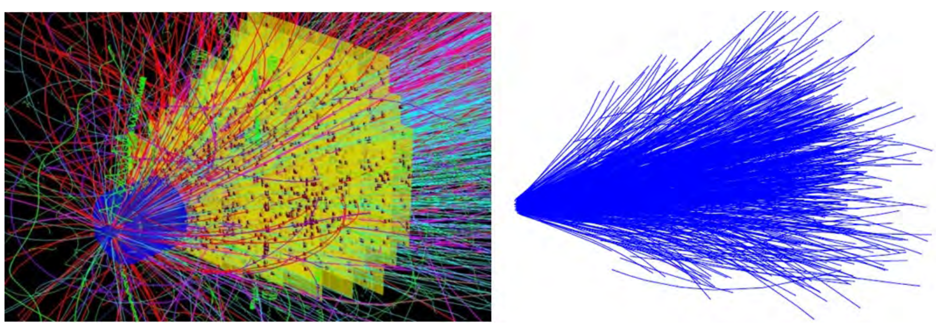


Fig. 4: The CBM experiment with the muon detection system in measuring position, and the RICH in parking position

plate chambers with low-resistivity glass for high-rate operation (up to 25 kHz/cm^2 with a time resolution of 50 ps), a Ring Imaging Cherenkov (RICH) detector and a Transition Radiation Detector (TRD) for electron identification, and a forward hadron calorimeter (Projectile Spectator Detector) for event characterization. The RICH detector can be replaced by a Muon chamber (MuCh) system for muon identification. The MuCh detector consists of 5 triple stations of highly granulated gaseous micro-pattern chambers detectors sandwiched by iron plates with a total thickness equivalent to 13 absorption lengths. Measuring both electrons and muons will dramatically reduce the systematic errors due to background subtraction - which is notoriously difficult - because the background sources of electrons and muons are completely different. All detector systems are equipped with self-triggered read-out electronics. After data compression and conversion into optical signals, the data are delivered via about 1000 m long fibres to the FAIR high performance computing cluster ("Green-IT cube") where the First Level Event Selection (FLES) will be performed. The development of the experimental components is well in progress. The Technical Design Reports (TDRs) on the Superconducting Dipole Magnet, on the Silicon Tracking System, on the Ring Imaging Cherenkov Detector, on the Projectile Spectator Detector, on the Time-of-Flight Detector, and on the Muon Chamber System have been approved by FAIR. The TDRs on Data Acquisition and First Level Event Selection, on the Micro-Vertex-Detector, and on the Transition Radiation Detector will be submitted in 2015. The actual status of the experiment preparation is documented in the CBM Progress Report 2013 (CBM Report, 2013).



A **B**

Fig. 5: (A) Simulation of a central Au+Au collision at a beam energy of 25 A GeV as seen by the Silicon Tracking System located inside the CBM dipole magnetic field. The particles are generated with the UrQMD code, and transported through the detector using the GEANT3 code. (B) Reconstruction of the event using the Cellular Automaton method for track finding and the Kalman Filter technique for track fitting

The optimization of the detector design has been carried out through extensive feasibility studies which are performed within a newly developed software framework ("FAIRroot"). The simulations involve event generators such as UrQMD and HSD, transport codes GEANT3/4 and FLUKA, and take into account realistic detector geometries, materials and response. Fig. 5 illustrates the performance of the track reconstruction algorithms in the Silicon Tracking System for a central Au+Au collision at an energy of 25 A GeV. The track reconstruction efficiency is better than 95%, the momentum resolution is between 1 and 1.5% for momenta between 0.5 and 10 GeV/c. Track reconstruction, searching for secondary vertices, particle identification using time-of-flight information, and calculation of invariant masses is performed by a high-speed algorithm running on many-core CPUs. The First Level Event Selection (FLES) package is vectorized, parallelized and scalable, more than 1600 events/sec can be processed by a single computing node with 80 cores. The algorithm provides invariant mass spectra of strange particles and resonances like K_s^0, K^{*-}, K^{*+}, ϕ, Λ, $\bar{\Lambda}$, Ξ^-, Ξ^+, Ω^-, Ω^+, Σ^{*-}, Σ^{*+}, $\bar{\Sigma}^{*-}$, $\bar{\Sigma}^{*+}$, Ξ^{*0}, $\bar{\Xi}^{*0}$, and others. Some of the results are presented in Fig. 6.

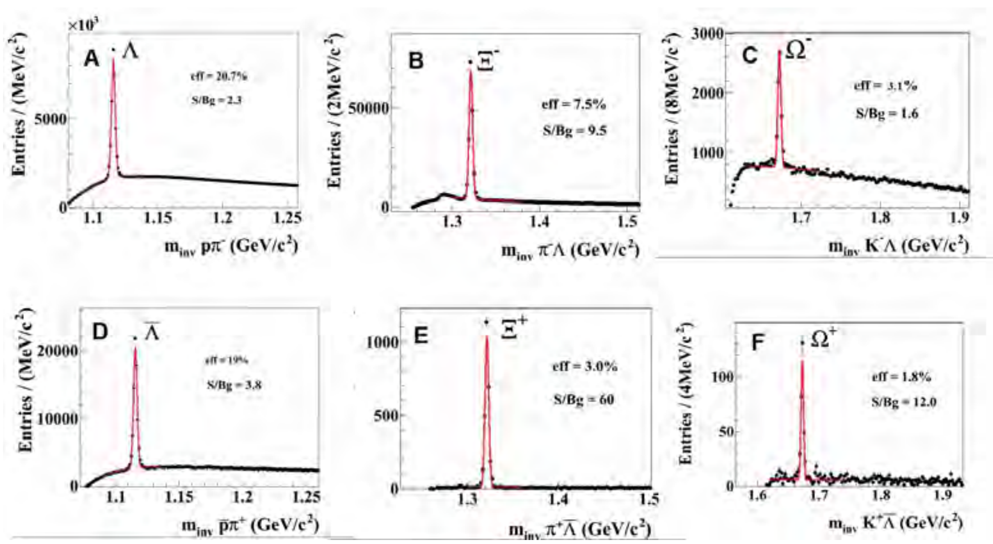


Fig. 6: Invariant mass spectra of $p\pi^-$ (A), $\pi^-\Lambda$ (B), $K^-\Lambda$ (C), $\bar{p}\pi^+$ (D), $pi^+\bar{\Lambda}$ (E), and $K^+\bar{\Lambda}$ (F) simulated and reconstructed for central Au+Au collision at a beam energy of 25 A GeV using the information from the STS and the TOF detector

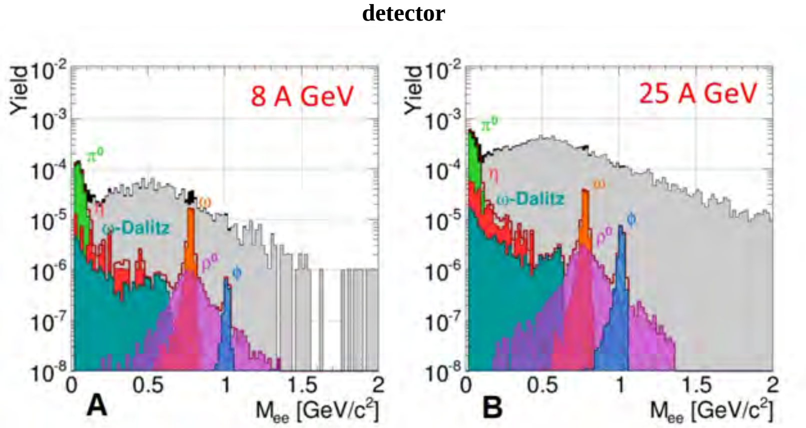
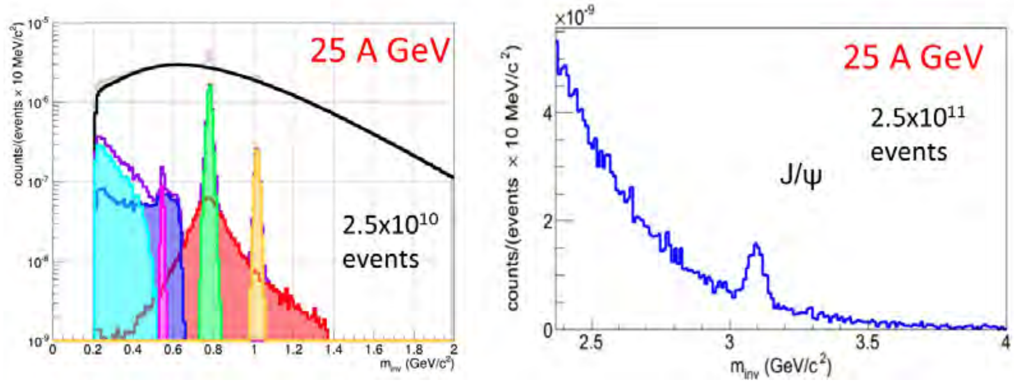


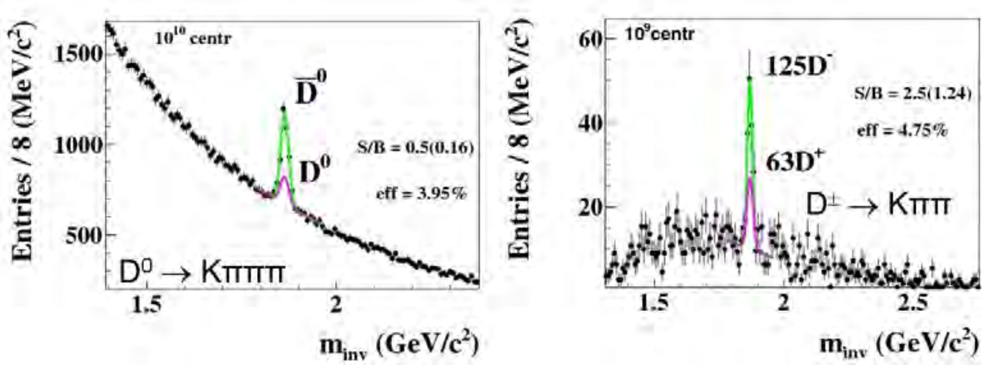
Fig. 7: Invariant mass spectra of electron-positron pairs simulated for central Au+Au collisions at 8 A GeV (A) and at 25 A GeV (B). Each spectrum corresponds to 250k events with a cut on $p_t > 0.2$ GeV/c for single electrons. Different signal sources are shown with different colors: from left to right: π^0-,η-, and ω-Dalitz decays, ρ-, ω-, and ϕ-meson

The CBM capabilities for dilepton measurements in central Au+Au collisions are demonstrated by the invariant mass spectra shown in Fig. 7 for low-mass electron-positron pairs, and in figure Fig. 8 for di-muon pairs. The simulations use the UrQMD code for background generation, and the HSD code for the yields of the signals which are imbedded in UrQMD events. The simulation and reconstruction of the electrons takes into account the information from the STS, RICH, TRD and TOF detector systems. The left panel of Fig. 7 depicts dielectron mass distribution for collision energies of 8 AGeV using 4 TRD layers, whereas in the right panel the distribution for 25 A GeV using 12 TRD layers is shown. Fig. 8 depicts the dimuon invariant mass distributions for collisions at 25 A GeV for the low mass region (A) and for the charmonium mass region (B). The simulations take into account information from the STS, the MuCh and the TOF detector.



A B

Fig. 8: Invariant mass spectra of muon pairs simulated and reconstructed for central Au+Au collisions at 25 A GeV in the low mass region (A) and in the charmonium mass region (B)



A B

Fig. 9: Invariant mass distributions of kaons and pions from D-meson decays simulated for central Au+Au collisions at 25 A GeV based on the information of the STS and the MVD (with two MAPS stations). Protons are rejected via TOF, no K and π identification is performed. (A): $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$, $\bar{D}^0 \rightarrow K^-\pi^+\pi^+\pi^-$, $c\tau = 123\mu$m, (B): $D^+ \rightarrow K^-\pi^+\pi^+$, $D^- \rightarrow K^+\pi^-\pi^-$, $c\tau = 317\mu$m

Summary

The Compressed Baryonic Matter (CBM) experiment will be one of the major scientific pillars of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of the CBM research program is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions. This includes the study of the equation-of-state of nuclear matter at neutron star core densities, and the search for the deconfinement and chiral phase transitions. The CBM detector is designed to measure rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics. Most of these particles will be studied for the first time in the FAIR energy range. In order to achieve the required precision, the measurements will be performed at reaction rates between 100 kHz and 10MHz. This requires very fast and radiation hard detectors, and a novel data read-out and analysis concept based on free streaming front-end electronics and a high-performance computing cluster for online event selection. The use of the most modern detector and computer technology is the prerequisite for a large discovery potential of heavy-ion collision experiments at FAIR energies.

Acknowledgments

The design and development of the CBM experiment is performed by the CBM Collaboration which actually consists of more than 500 persons from 57 institutions and 12 countries. The CBM project is supported by the German Ministry of Education and Research, the Helmholtz Association, the EU I3Hadronphysics3 programme, and national funds of the CBM member institutions.

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